Cognitive Effort Modulates Frontal Effective Connections

Katharina Wegner (katharina.wegner@ugent.be)
Ghent University, Henri Dunantlaan 2
9000 Ghent, Belgium

Charlie Wilson (charles.wilson@inserm.fr)
Inserm U1028, 95 Bd Pinel,
69675 Bron Cedex France´

Emmanuel Procyk (emmanuel.procyk@inserm.fr)
Inserm U1028, 95 Bd Pinel,
69675 Bron Cedex France´

Karl Friston (k.friston@ucl.ac.uk)
UCL Wellcome Centre for Human Neuroimaging, 12 Queen Square
London, United Kingdom WC1 3BG

Daniele Marinazzo (daniele.marinazzo@ugent.be)
Ghent University, Henri Dunantlaan 2
9000 Ghent, Belgium

Abstract:

Frontal beta band power has been shown to increase both as a consequence of elevated task demands and with time on task. Beta band power may thus be a neural correlate of cognitive effort. The present study report effective connections between the prefrontal and premotor cortex, areas known to be involved in cognitive control, and shows that these effective connections change in line with frontal beta band power. The changes in frontal connections, however, are unrelated to signs of mental fatigue. The interactions between task-relevant brain areas may thus be related to cognitive effort and not mental fatigue.

Keywords: **cognitive control; cognitive effort; beta power; effective connectivity;, time-on-task; dynamic causal modeling; parametric empirical Bayes**

Introduction

When a cognitive task needs to be executed continuously over time, focusing on the task may become more challenging due to the emergence of mental fatigue. This time-on-task effect manifests itself as increasing reaction time and errors over time (Boksem et al., 2005; Lorist et al. 2009). Cognitive effort is the activity needed for the successful performance of a cognitive task and may serve as a compensatory mechanism of fatigue to enable the maintenance of the current performance level over time. To this date, the neural underpinnings of cognitive effort and how these can be distinguished from the underpinnings of mental fatigue are not well understood.

Some studies suggest that task-relevant processes increase with the amount of processed information, an effect that can be attributed to the increase of cognitive effort. For example, Koechlin and colleagues (2003) manipulated task demands by varying the perceptual and temporal context of the stimulus-response mapping and found increasing fMRI activations in the lateral prefrontal and premotor cortex with increasing information to be processed. A study on macaque monkeys by Stoll and colleagues (2016) showed the involvement of frontal beta band power during task preparation. Beta band power has previously been associated with top-down control (Engel and Fries, 2010). Interestingly, beta-band activity was elevated both when the task demands were higher and as the session progressed. Frontal beta band power may thus be a neural correlate of cognitive effort.

We propose that information processing over time among task-relevant areas are modulated by cognitive effort and not by signs of mental fatigue. To test this hypothesis, we applied dynamic causal modeling (DCM) to the dataset of Stoll and colleagues (2016) in order to estimate effective connections among task-relevant brain regions (prefrontal and premotor cortex). By testing whether shapes of cognitive effort (beta band power over time) and shapes of mental fatigue (reaction time) can explain changes in effective connectivity strength, we investigated the involvement of the areas in cognitive effort and mental fatigue.

Methods

Subjects and Data

Two macaque monkeys were implanted with 22 to 29 frontal and sensorimotor electrodes (see Figure 1). The experiment spanned over several weeks and data for 19 days are available and analyzed.

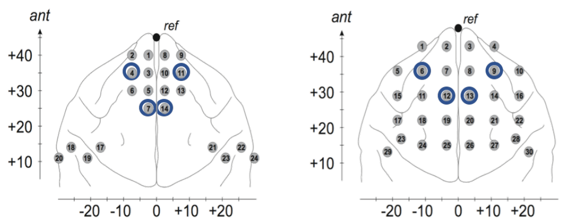

Figure 1: Electrode grids and selected electrodes (blue circles).

1st Level Analysis: DCM For Cross-Spectral Density

DCM is a Bayesian framework that infers the causal architecture within and between regions. Each region is modelled as a canonical microcircuit, by which the activity and interactions between neural subpopulations can be estimated (Friston et al., 2003; see Fig. 2). DCM distinguishes between forward and backward connections among regions that are distinct due to their origin or target neural population. Among competing model architectures the best model is chosen via Bayesian model comparison.

To model interactions between the lateral prefrontal cortex and premotor area, we selected electrodes that were close to these areas and similar between subjects (see Figure 1). Three different model architectures were established (see Figure 2). For each session and each subjects, trials were divided into eight bins and DCMs of these different model architectures were inverted for each bin. To have strong evidence in favor of one model, a model with model evidence that was larger by a factor of at least 20 was considered the winning model and used for the 2nd level analysis.

2nd Level Analysis: Parametric Empirical Bayes

In order to test which effective connections consistently change across bins in line with shapes of cognitive effort and mental fatigue, parametric empirical Bayes (PEB) was applied. This approach is similar to a regression analysis with time shapes of cognitive effort and mental fatigue as the independent variable and connectivity strength across time bins as the dependent variable. One essential difference of PEB to a frequentist regression is that the precision parameters of the first level are taken to the second level analysis (Friston et al., 2016). We tested the following hypotheses: (1) Changes in effective connections between the prefrontal and premotor cortices can be explained by changes in beta band power, (2) changes in effective connections between the prefrontal and premotor cortices can be explained by changes in reaction times. The resulting parameter probability indicates for each independent variable the certainty with which the changes in the respective effective connection can be explained by the independent variable.

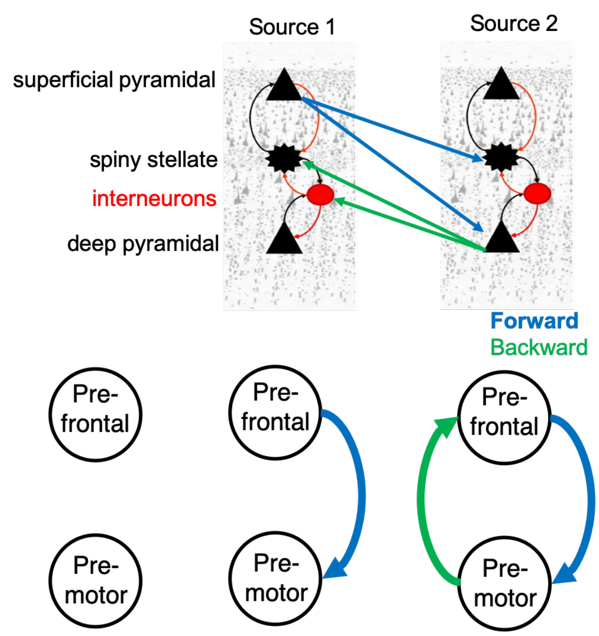

Figure 2: Effective connectivity within and between sources and proposed model architectures

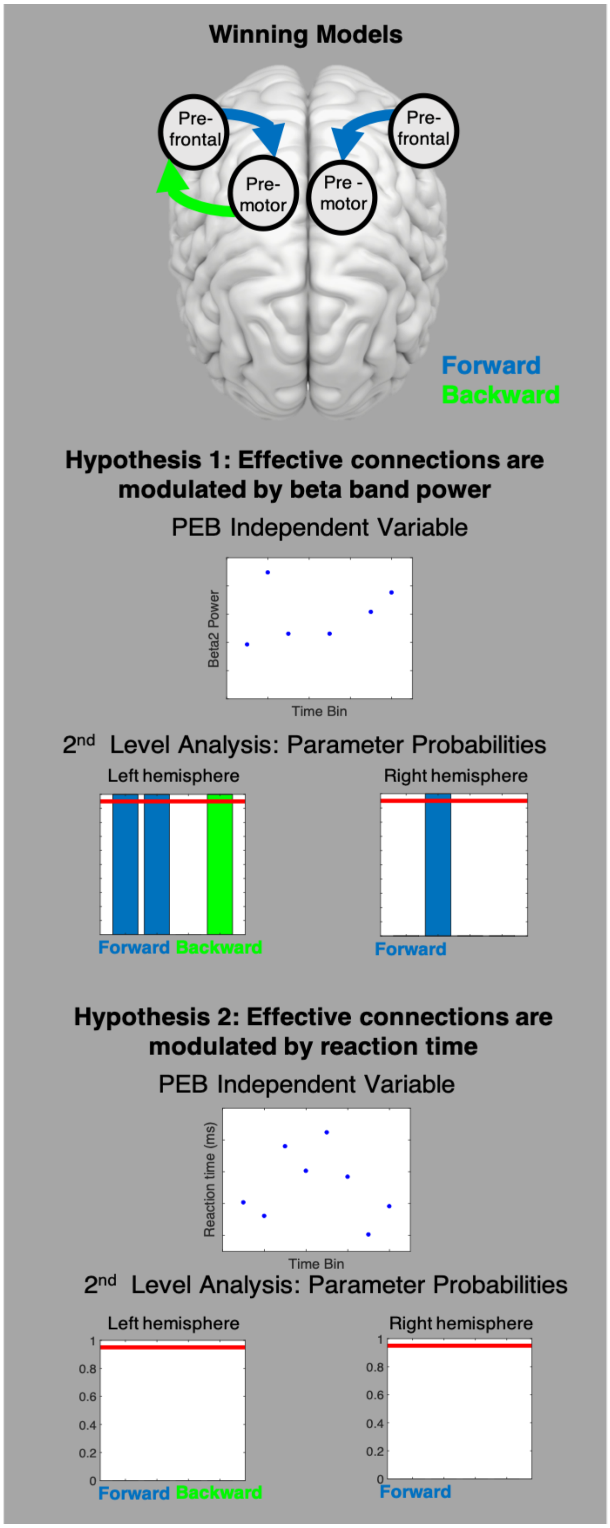

Figure 3. DCM and PEB results: Winning DCM model architectures and PEB parameter probabilities.

Results

1st Level Analysis: Winning Model Architecture

The Bayesian model comparison yielded different winning models in each hemisphere. In the left hemisphere, a full model was 100 percent more likely than the remaining models. In the right hemisphere, a forward model was 91 percent more likely than the remaining models (0 percent for the no-connectivity model, 9 percent for the fully connected model).

2nd Level Analysis: Parameter Probabilities

A PEB analysis with beta band power as independent variable showed that changes of almost all effective connections are explained by beta power. Figure 3 contains parameter probabilities resulting from the PEB analysis. Bars exceeding the red line indicate that the respective effective connection is related to the input variable with 95% certainty. Using reaction time as independent variable, however, has shown that changes in effective connections cannot be explained by reaction time, as can be shown by the lack of parameter probabilities.

Discussion

We found effective frontal connections between the prefrontal and premotor cortex. While in the right connections, we found a forward connection from the prefrontal to the premotor area, the data indicate an additional backward connection in the left hemisphere. Further studies are needed to show whether this asymmetry across hemispheres is persistent across more subjects.

As the session of the cognitive task progressed, the effective connections between the prefrontal and premotor cortex fluctuated and these fluctuations were in line with the increase in beta band power, but not with the increase in reaction time. If we assume that beta band power is a proxy of cognitive effort and reaction time is a proxy of mental fatigue, we can conclude that effective connections between task-relevant brain regions are modulated by cognitive effort and not by mental fatigue.

References

Boksem, MA, Meijman, TF, & Lorist, MM (2005). Effects of mental fatigue on attention: an ERP study. Cognitive brain research , 25 (1), 107-116.

Engel, A. K., & Fries, P. (2010). Beta-band oscillations—signalling the status quo?. Current opinion in neurobiology, 20(2), 156-165.

Friston, K. J., Harrison, L., & Penny, W. (2003). Dynamic causal modelling. Neuroimage, 19(4), 1273-1302.

Friston, K. J., Litvak, V., Oswal, A., Razi, A., Stephan, K. E., van Wijk, B. C. & Zeidman, P. (2016). Bayesian model reduction and empirical Bayes for group (DCM) studies. Neuroimage, 128, 413-431.

Lorist, M. M., Bezdan, E., ten Caat, M., Span, M. M., Roerdink, J. B., & Maurits, N. M. (2009). The influence of mental fatigue and motivation on neural network dynamics; an EEG coherence study. Brain Research, 1270, 95-106.

Stoll, F. M., Wilson, C. R., Faraut, M. C., Vezoli, J., Knoblauch, K., & Procyk, E. (2015). The effects of cognitive control and time on frontal beta oscillations. *Cerebral Cortex*, *26*(4), 1715-1732.